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COMPLETE SPECIFICATION

Nuclear Magnetism Well Logging Apparatus

We, CALIFORNIA RESEARCH CORPORATION, a corporation organized and existing under the laws of the State of Delaware, United States of America, of 200, Bush Street, San Fransisco 4, State of California, United States of America, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

This invention relates to a method and an apparatus for locating and differentiating substances by their nuclear magnetic resonance properties and, more particularly, is concerned with a method and logging apparatus for locating hydrogenous fluids and distinguishing between water and oil in an earth formation around a bore hole.

It is an object of the invention to provide an apparatus suitable for use in carrying out a method of nuclear magnetism well logging for determining the total liquid content in an earth formation traversed by a well bore, independently of the shape and size of the bore hole, by determining the density of responsive protons in the drilling fluid utilized in said well bore and then determining separately the amplitudes of nuclear magnetic signals from both the drilling fluid in the bore hole and the liquids in the formation, to determine the density of responsive protons in the formation as a direct measurement of the liquid content of said formation.

According to one aspect of the invention there is provided a method of locating the presence of a natural hydrogenous fluid in association with another natural hydrogenous fluid within an earth formation penetrated by a well bore, which comprises the steps of:—

(a) establishing a magnetic polarizing field in said earth formation from within said well bore to polarize the nuclei of hydrogen atoms of said hydrogenous fluids within said earth formation, said polarizing field being oriented at an angle to the earth's magnetic field within said earth formation,

(b) interrupting said polarizing field rapidly to permit said nuclei to precess about the earth's magnetic field within said formation,

(c) detecting nuclear magnetic precessional signals from said precessing nuclei, and

(d) measuring a characteristics of the detected precessional signals as an indication of the relaxation time of said hydrogen nuclei in the earth's magnetic field, whereby a comparison may be made between the indication of the relaxation time of said hydrogen nuclei in said earth formation and the relaxation time of hydrogen nuclei in a known hydrogenous fluid.

The present invention also provides an apparatus for use in nuclear magnetism well logging which comprises a coil adapted to be positioned in a well bore for polarization of nuclei in and around said well bore and a source of DC power conductively connected with said coil, one dimension of said coil perpendicular to its axis being great in comparison to the other dimension of the coil which is perpendicular to the axis and to said one dimension, means for initiating current flow from the DC power supply to said coil, means for stopping the flow of DC power to said coil, and means for detecting nuclear magnetic precessional signals from precessing nuclei.

It is a further object of the invention to provide an improved method, and an apparatus for carrying out such method, of distinguishing whether protons, within fluids in and around a well bore, are contained in water or in hydrocarbons by introducing into the drilling fluids present within said well bore a ferromagnetic material or a para-

magnetic material so that water and oil may be distinguished even when the physical environment of temperature and pressure would normally cause the protons within these fluids to have substantially the same relaxation times.

In a preferred embodiment, a paramagnetic material in molecular form, such as molecular oxygen, which is soluble in water and substantially insoluble in hydrocarbons is introduced into the drilling fluids.

In order to explain the invention, it is necessary to set forth in a brief fashion the elementary nuclear theory on which our method is based. An atom consists of a small, heavy, positively charged center called the nucleus surrounded by a relatively extensive diffuse cloud of electrons. The nucleus carries a positive charge equal to the negative charge of the external electrons and has a spin or angular momentum which varies with the nature of the nucleus. The hydrogen nucleus, for example, has an angular momentum $a = \frac{\frac{1}{2}h}{2\pi}$ where h is the well known Planck's Constant. In this sense, the nucleus which in the case of the hydrogen atom is a proton, acts like a small gyroscope. The proton has a characteristic magnetic moment, μ, which is a measure of the proton's tendency to line up with a magnetic field while the nucleus of the hydrogen atom consists of a single proton, nuclei of other atoms contain more than one proton, together with varied numbers of neutrons. Some nuclei do not have a spin and, hence, a magnetic moment, although they do contain varying numbers of protons. In carrying out the present invention only those nuclei possessing magnetic moments, and especially protons, are detected from within the well bore.

In substances on which our invention is to be employed, the nucleus is not affected solely by an external magnetic field. Rather, the total field which acts on a nucleus is the sum of the external fields plus a local field peculiar to the nucleus under study. The local field is affected by the proximity of other nuclei and electrons. The effective magnetic field acting on one nucleus is different from that acting on other nuclei in the same sample. Consequences of these facts will be discussed more fully in later portions of this application.

In the absence of an external magnetic field, the nuclei of any sample of material are randomly oriented in space. When an external magnetic field is impressed on the sample, the nuclei are subjected to a torque proportional to their magnetic moments and tend to align themselves with the magnetic field. In the case of protons, the magnetic moments can align themselves either in the direction of the field or in the direction opposed to the field, but the protons are in the lower energy state if aligned in the direction of the field. Accordingly, a few more of the protons will align themselves with the field than will align themselves against the field.

According to classical theory, the nuclear resonance process may be visualized in the following manner: In the presence of a magnetic field, the nuclei do not merely swing into position with the field, but tend to precess around the field. In this, the nuclei resemble a gyroscope which is acted on by the earth's gravitational field. The earth's gravitational field exerts a torque on the gyroscope tending to cause the gyroscope to align itself with the earth's gravitational field. This torque on the gyroscope causes precession about the direction of the earth's gravitational field as the gyroscope seeks a position in the direction of the earth's gravitational field. Analogously, those nuclei which have a spin and associated magnetic moment tend to precess about the direction of the external magnetic field as they seek a position parallel to the field. This precession is in response to the torque exerted on their magnetic moments. The orderly precession of the nuclei is interrupted by thermal agitation and effect of adjacent precessing nuclei. The effective magnetic field on each nucleus is a combination of the external magnetic field and the resultant magnetic field due to the combined effect of the magnetic fields of adjacent charged particles. The proximity of the charged particles to a given nucleus varies with time and tends to interfere with the precession and to prevent rapid alignment of the nuclei with the magnetic field.

The natural frequency of precession of nuclei within an external magnetic field is determined by the nature of the nuclei and the strength of the magnetic field. This natural frequency is called the Larmor frequency. The Larmor frequency is $\omega_L = \frac{\mu}{a} H$. H is the field at the position of the nucleus and is the vector sum of the magnetic field applied externally and the magnetic fields of adjacent charged particles. The ratio of μ to a is commonly denoted by the symbol γ and is called the gyromagnetic ratio of the particular nucleus in question. γ, then, determines the precessional frequency of nuclei for a given external magnetic field.

Nuclei precessing about a magnetic field are equivalent in some respects to rotating magnetic dipoles and as such are capable of inducing a signal in a coil. Nuclei which are precessing about a magnetic field are, in general, oriented randomly with respect to a predetermined direction perpendicular to the field. Thus, a pickup coil which receives a signal due to the precession of one nucleus

receives an equal and opposite signal from some other nucleus. The macroscopic effect is a complete cancelling out of signals from individual nuclei. An adjacent pickup coil can receive no signal from the precessing nuclei unless there is a precessing macroscopic moment.

A number of methods have been found for causing the nuclei to precess in phase to provide a precessing macroscopic moment. One method is disclosed in our invention and will be described later, although our invention is not limited thereto.

In the preferred method of practicing this invention, a condition of nuclear precession is established in the formation adjacent the bore of a well. A macroscopic precessing moment is produced by a polarizing field. The polarizing field is caused to collapse and the relaxation time of the precessing nuclei is measured as an indication of the nature of the liquids in the formation.

The novel features of our invention are set forth with more particularity in the accompanying claims. The invention itself, however, with respect to the details thereof, together with its additional objects and advantages, may be better understood from the following description of specific embodiments with reference to the accompanying drawings, in which:—

Fig. 1 is a schematic circuit diagram of an exemplary embodiment of a nuclear magnetic induction logging instrument according to our invention.

Fig. 2 is a schematic circuit diagram of a suitable fast electrical switch.

Fig. 3 is a vector diagram of the macroscopic moment, and the fields acting to orient the macroscopic moment.

Fig. 4 is a graph of signal voltage versus time for only one hydrogenous fluid.

Fig. 5 is a schematic representation of a well bore illustrating a preferred form of a single coil apparatus that is particularly useful to determine porosity and fluid content of earth formations, independently of the shape and size of the bore hole passing therethrough.

Fig. 6 is a diagrammatic representation of the type of nuclear magnetic relaxation time signal obtained when a strong polarizing magnetic field, applied to a body of fluid, is suddenly removed and the protons of the fluid are allowed to precess in the earth's magnetic field.

Fig. 7 is similar to Fig. 8, but represents a fluid having a different relaxation time.

Fig. 8 is a diagrammatic representation of a modified nuclear magnetism signal obtained with apparatus of the present invention when two different fluids, such as the drilling fluid in the bore hole, and the fluids of a formation, have sufficiently different relaxation times to permit separate identification of the amplitude contribution of the formation fluid, and also that of the drilling fluid.

It will be noted that each of the Figs. 6, 7 and 8 is semi-logarithmic. The ordinates represent logarithms of signal amplitudes and the abscissas represent time on arithmetic scale.

As shown in Fig. 1, a DC power supply 11 provides direct current to a polarizing coil 15 through a fast switch 13. A pulse generator 17 controls the fast switch 13 and a gated preamplifier 19. A detector coil 21 is connected in parallel with a capacitor 23 and feeds into the gated preamplifier 19. The preamplifier 19 feeds current through a band-pass amplifier 25 to an oscillograph 27.

The pulse generator 17 generates a negative-voltage square wave. It is adapted to be adjustable so that the duration of the negative pulse and of the interval between pulses from the generator 17 may be varied over a substantial range. The pulse generator is so connected into the preamplifier 19 that it gates the preamplifier 19. The pulse generator 17 also controls the fast switch 13.

Referring to Fig. 2, the pulse generator 17 controls the voltage of the grid 31 of a vacuum tube 33. The DC power supply 11 is connected through the coil 15, through a resistor 35 and vacuum tube 33 to ground. The resistance of the resistor 35 is sufficiently high that for nuclear polarization purposes it may be regarded as an open circuit. To initiate current flow through the coil 15, the tube 33 is rendered conductive by a change in voltage impressed by the pulse generator 17. A later change in the voltage on the grid 31 renders the vacuum tube 33 non-conductive. The resistor 35, shunting the tube 33, serves to limit the voltage across the tube 33 resulting from the rapid reduction in DC current through the inductor 15.

The current through the polarizing coil 15 shown in Fig. 1 sets up in the formation adjacent to the well which is being logged a magnetic field which establishes a macroscopic nuclear magnetic moment with a component perpendicular to the earth's magnetic field. If the magnetic field of the coil 15 is removed quickly enough, the macroscopic moment will precess about the earth's magnetic field. It is important to the successful operation of the invention that the polarizing coil is designed to permit extremely rapid decay of the polarizing field as compared to the Larmor period of a proton in the earth's magnetic field.

The gated preamplifier 19 is also controlled by the pulse generator 17 and is gated off until the DC polarizing field has reached zero. This is done to prevent the voltages induced in the detector coil by the switching of the polarizing coil from blocking preamplifier 19 and the amplifier 25.

As soon as the DC polarizing field of the

coil 15 is effectively zero, the nuclear signals are picked up by the tuned detector 21—23, amplified, and recorded on the oscillograph 27. The coil 21 detects the signal from precessing protons in a manner somewhat similar to the action of a transformer secondary. The angle θ between coil 21 and coil 15 may have an arbitrary value. When it is desired to minimize the signal induced in coil 21 by coil 15, θ should be equal to 90 degrees. However, the signal induced in coil 21 by oscillations in coil 15 during shut-off of coil 15 can be damped while the preamplifier 19 is gated off. The capacitor 23, in conjunction with coil 21, forms a tuned circuit. The oscillograph may be either a cathode ray oscilloscope, the face of which is photographed in order to record the signal on its face, or the oscillograph may be another type of recording oscillograph.

It is not necessary that coil 15 and coil 21 be physically separate coils. A suitable single coil form of a logging instrument is shown in Fig. 5 and will be described in detail below.

The operation of the apparatus described with reference to Fig. 1 will now be described. First, it is necessary to define relaxation time and present the scientific basis on which an analysis of the signal output of the above-described apparatus may be made.

When a magnetic field is applied externally to a sample, the rate at which the nuclear magnetic moment reaches an equilibrium value is an exponential function of time and is characterized by the thermal relaxation time commonly denoted by T_1:—

$$M=M_i+(M_t-M_i)\ (1-e^{-t/T_1})$$

where M is the nuclear magnetic moment, M_i is the initial moment of the system at the instant the external magnetic field is applied, and M_t is the final equilibrium moment of the system of nuclear magnetic moments. When the nuclei are caused to precess in phase, a net macroscopic precessing nuclear magnetic moment arises. The precessing component of the macroscopic moment is gradually destroyed over a period of time by thermal motion of the nuclear moments and by the interaction of the nuclear magnetic moments among themselves at a rate that is an exponential function of time. The rate is characterized by the relaxation time T which is determined both by T_1, defined above, and by T_2, where T_2 characterizes the rate at which the precessing nuclei get out of phase because of the interaction of their nuclear magnetic moments.

T_1 and T_2 are characteristic of a particular hydrogenous fluid, being determined by viscosity, temperature, paramagnetic impurities, electronic magnetic fields, and interaction of nuclear magnetic moments. In particular, the protons in oil within the formation will have a different relaxation time T from that of the protons in water within the formation. A number of characteristic differences between oil and water are either concomitant with this effect or cause a change in the relaxation time. Oil, having a different chemical composition from water, tends to imbue its protons with a somewhat different relaxation time. At atmospheric pressures and temperatures, crude oil has a higher viscosity than water and tends, for this reason, to have a shorter relaxation time. However, these considerations are characteristic of differences between oil and water in the pure form. Oil and water within the earth, on the other hand, contain a wide assortment of impurities. Paramagnetic and ferromagnetic impurities within a hydrogenous liquid can shorten the relaxation time of the protons therein. A very small quantity of such paramagnetic or magnetic impurity in the liquids has a gross effect on the relaxation time. Thus, the amount of these magnetic impurities within the formation waters or crude oil will determine whether oil or water will have the longer relaxation time. In general such materials predominate in water as compared to oil in earth formations so that the relaxation time for water is normally shorter than for oil.

There will be no nuclear magnetic resonance of carbon or oxygen in the formation, since the angular momentum and magnetic moment of the nuclei of these two elements is zero. Solid substances not suspended in liquids within the formation do not provide a resonance signal sufficient to interfere with the nuclear resonance signal to which our present invention pertains. In some situations it is difficult to differentiate oil or water in the drilling mud from that in the formation. Under those circumstances, it is advisable to introduce an amount of paramagnetic impurity into the drilling mud sufficient to greatly shorten the relaxation time of protons therein. Then, the signal from the processing nuclei of the mud will decay so rapidly that it will be insufficient to interfere with the signal picked up from the precessing nuclei in the formation. Furthermore, the additive may be so chosen that the drilling fluid filtrate has a negligible relaxation time so that nuclear resonance signals from the zone of formation around the bore hole invaded by filtrate will give rise to signals from only crude oil and water originally in situ. Furthermore, if water base drilling mud is used, the additive can be so chosen that the signal from the crude oil remaining in the invaded zone is not influenced.

Water soluble paramagnetic ions can be introduced into the drilling fluid to modify the signal obtained from the drilling fluid in the well bore and the drilling fluid filtrate

that may invade the formations adjacent the bore hole. However, the physical characteristics, and particularly the fluid properties, of the drilling fluid are very sensitive to the kind and concentration of ions in the liquid phase. Accordingly, the introduction of some paramagnetic ions, such as iron, cobalt, nickel, copper and the like, have a tendency to adversely affect the electrical properties of the drilling fluid so that normal electrical logging of the well bore is quite difficult, if not impossible.

In accordance with one method of carrying out the present invention, it is possible to modify the relaxation times of the protons within the fluids in and around the well bore without adversely affecting the physical and electrical properties of the drilling fluid by introducing a molecular paramagnetic material, such as molecular oxygen, into the well bore fluid. Desirably, the molecular paramagnetic material is preferentially soluble in one or the other of the two liquids to be distinguished, oil and water. In the case of molecular oxygen, this paramagnetic material is selectively soluble in water. The molecular oxygen may be introduced either directly into the well fluid as a pure gas, or in a gaseous or liquid mixture with inert materials, such as air, or may be introduced by a compound such as hydrogen peroxide which is capable of liberating molecular oxygen.

In carrying out the method of the present invention, it is possible to introduce the molecular paramagnetic material into the drilling fluid for the purpose of modifying the relaxation time of protons contained in the drilling fluid water during some or all of the time the well is being drilled. In this way, the molecular paramagnetic material is dissolved in the water of the drilling fluid and is able to penetrate through the filter cake and even invade the porous formations lying along the well bore, particularly those permeable formations containing water in an unbound or free state. Once the fluid containing the dissolved molecular paramagnetic material has passed through the filter cake and invaded the permeable formations adjacent to the well bore, that molecular paramagnetic material is free to diffuse throughout any fluid forming a continuous phase with the invading fluid and thus to influence the nuclear magnetic relaxation time of all protons contained in that fluid phase, regardless of whether said protons were originally present in the formation or were introduced during the act of drilling the bore hole.

Alternatively, the modification of the nuclear magnetic relaxation time of the protons in the drilling fluid may be affected by introduction of the molecular paramagnetic material into the drilling fluid after completion of the drilling operation. Particular portions of the well bore fluids may thus be selectively treated by the introduction of the molecular paramagnetic material through the drill string, while it is being removed from the bore hole and prior to the logging operation.

The actual manner of introducing the molecular paramagnetic material is immaterial to the present invention. It may be accomplished while the drilling mud is at essentially atmospheric pressure by introduction into the surface circulating and storing facilities normally associated with the drilling operation. It may also be injected under pressure into the drilling fluid stream as the fluid passes from the pumps and immediately prior to its entry into the drill pipe. This latter method is particularly advantageous where the molecular paramagnetic material is a gaseous material. In this way, not only the bulk volume of molecular paramagnetic material to be handled at the well site is reduced by compression of the gaseous material, but also the solubility, and thus the effective concentration, is increased by injection into the fluid at high pressure.

In the practice of this invention, molecular oxygen is a very suitable molecular paramagnetic material, since it does not adversely affect the electrical and fluid properties of the drilling fluid. Additionally, it is readily available in various forms, such as atmospheric air, compressed air, and compressed or liquid oxygen. It may be also be supplied in a chemically bound form by materials such as hydrogen peroxide, which although not paramagnetic itself can be readily induced to decompose to form molecular oxygen in drilling fluid, after injection. Slightly ionized molecular paramagnetic materials, which do not affect the electrical current carrying characteristics of the mud, can also be used without seriously affecting the electrical properties of the mud.

In the practice of this invention, the earth's magnetic field, H_e, is employed as the external magnetic field. Protons within this field have ample time to align themselves in the direction of the field. Accordingly, relaxation time is not of interest in the mechanism of the original alignments. As indicated previously, a slightly larger number of the protons have been aligned in the direction opposite to the field. If a second DC magnetic field is impressed on a sample at an angle with the earth's magnetic field, the resultant magnetic field, $\overline{H_r}$, is at an angle to both the earth's magnetic field and the second magnetic field, $\overline{H_p}$, as shown in Fig. 3. Nuclei now tend to align themselves with the resultant magnetic field, $\overline{H_r}$. The preponderance of nuclear magnetic moments aligned with the

field $\underline{H}_r$ gives rise to a changed orientation and magnitude of the macroscopic moment. The changeover of the macroscopic moment from the direction, $\underline{H}_e$, to the direction $\underline{H}_r$, does not occur instantaneously, the time taken being given by the equation

$$\underline{M}=\underline{M}_o(1-e^{-t/T_1})+\underline{M}_e$$

where $\underline{M}$=the macroscopic moment vector in the direction of H_r

$\underline{M}_o$=a known vector=X $(\underline{H}_r-\underline{H}_e)$

t=time

M_e=vector component of macroscopic moment in the direction of the earth's field

T_1=thermal relaxation time

X=nuclear magnetic susceptibility of the interstitial fluids in the formation surrounding the bore hole.

After an interval of time, the protons reach a steady state where the macroscopic moment in the direction, $\underline{H}_r$, is essentially equal to $\underline{M}_o$, if, as will be the case in the operation of apparatus according to our invention, $\underline{H}_p$ is much greater than $\underline{H}_e$.

When the field H_p is removed, the macroscopic moment tends to align itself with $\underline{H}_e$ and to be reduced to its original value $\underline{M}_e$. If $\underline{H}_p$ is removed quickly enough (in a time short compared to $1/\omega_L$, where ω_L is the Larmor frequency of a proton in the earth's magnetic field), then the macroscopic moment will precess about $\underline{H}_e$. $1/\omega_L$ is about one-twentieth of a millisecond for protons in $\underline{H}_e$. $\underline{H}_p$ may be about ten gauss while $\underline{H}_e$ is of the order of one-half gauss. In order for precession to occur, $\underline{H}_p$ must be reduced from about one gauss to much less than one gauss in a time of the order of one-twentieth of a millisecond or less. The pickup coil 21 in the vicinity of the sample is capable of detecting the precession of the macroscopic moment. As the macroscopic moment precesses, it tends to align itself with $\underline{H}_e$ and the protons tend to assume a random position with respect to the plane perpendicular to the axis of precession. Due to these effects, the signal received by the pickup coil decreases according to the equation

$$V=Be^{-t/T},$$

where: V=signal voltage

B=an arbitrary constant

T=relaxation time

t=time

Fig. 4 shows a graph of V versus t, of which the above equation gives the envelope. As discussed previously, the relaxation time, T, which appears in the above equation, depends on both the thermal relaxation time T_1 and the spin-spin relaxation time T_2, while the relaxation time which controls the time required for the protons to align themselves with the resultant field, H_r, is the thermal relaxation time.

The oscillograph records a signal such as that shown in Fig. 4. The record shown in Fig. 4 is interpreted as follows: a measurement is made of the peak to peak amplitudes which are then correlated to obtain the constants which appear in the equation $V=Be^{-t/T}$. In this equation, the constant T is the quantity to be determined. This is the relaxation time. If the signal shows the combined effects of two relaxation times present simultaneously for a heterogeneous mixture of two different fluids, the signal can be analyzed in a manner, discussed below in connection with Figs. 6 to 8, for the values of the two relaxation times.

The above description of the manner of analyzing the record on the oscilloscope was based on operating the pulse generator 17 with off times of uniform length sufficient to permit time for the nuclei to align themselves with the resultant field $\underline{H}_r$. By the above procedure, the signal decay relaxation time is measured. As an alternative, the polarization time may be measured. To measure the polarization time, the pulse generator is adjusted to emit pulses at intervals varying in a predetermined manner. The duration of each successive off time is greater than the duration of the previous off time by a discrete amount. The signal from the precessing nuclei is picked up by the coil 21 as before and recorded in the oscillograph. At the end of a very short pulse from the coil 15, the maximum amplitude of the signal picked up by the coil 21 is not as high as it would be when the magnetic moment in the direction $\underline{H}_r$ has reached a high value. The longer the pulse is from the polarizing coil 15, the greater will be the maximum amplitude of the voltage recorded on the oscillograph 27. Thus, if a number of records are taken on the oscillograph which result from pulses of varying duration, data can be obtained from which one may plot a graph of maximum signal voltage versus polarizing time. From this graph the thermal relaxation time T_1 can be obtained. This quantity T_1 has the same usefulness in distinguishing water and oil in a formation as does the determina-

tion of the relaxation time which is measured after the DC power is turned off. The presence of two values of T_1 originating from crude oil and formation water may be determined, and the values of T_1 measured in a manner apparent from the method of determining T set forth above.

The quality of the signal recorded on the oscillograph and its usefulness in determining the types of fluids in the formation are dependent in part on the depth to which the DC field of the polarizing coil 15 penetrates into the formation. It is important, therefore, that the coil 15 be of such a nature as to provide the maximum penetration consistent with establishing a detectable nuclear resonance signal. In our apparatus the polarizing coil is a flat rectangular coil of great length and of the maximum width consistent with bore hole size. Except at positions near the ends of the polarizing coil, the field due to this coil is nearly the same as that produced by two parallel wires of infinite length, i.e., its long dimension is great compared with the diameter of its field of polarization. This field drops off more slowly with distance from the coil than does the field of a circular winding. Our coil permits sampling deeper into the formation and gives a stronger nuclear resonance signal than a circular winding. The pickup coil 21 has a length along the axis of the well less than the thickness of the thinnest structure that one seeks to identify. Desirably, it is also sufficiently shorter than the polarizing coil 15 to avoid end effects.

In the description of the foregoing embodiment, a characteristic of the relaxation times, such as amplitude or duration of the signal, is used to distinguish nuclear magnetic signals from oil and water. In the following description, relating to use of the embodiment illustrated in Fig. 5 and demonstrated in Figs. 6 to 8, such use is not contemplated as the primary aspect of the method. It is necessary in said use, however, that there be two distinguishable relaxation times, one being that of the fluid in the bore hole and the other being that of the fluid in the formation surrounding the bore hole. It is necessary that these two relaxation times be different enough to permit separate measurement of the amplitudes of the respective signals, but as long as they are different enough there is no primary need to measure the relaxation times themselves quantitatively. However, under certain conditions the present method may be used in conjunction with relaxation time measurements to distinguish additionally between oil and water.

The arrangement shown in Fig. 5 is especially useful in distinguishing such two different relaxation times by measuring the density of responsive protons in the formations through a sequence of steps discussed below.

The term, density of responsive protons, as used herein refers to the number of protons per unit volume in the material being investigated, and more exactly to the number of protons, or hydrogen nuclei, per unit volume, that are free to react to imposed magnetic fields so as to give useful nuclear magnetic signals. Ordinarily, all protons contained in the molecules of fluids are such responsive protons. The word "responsive" is used here specifically to exclude those protons that are bound into molecules of solid materials, or into molecules of ordinarily fluid materials that themselves are bound or adsorbed into or onto solid materials by strong physical or chemical forces so that their protons cannot freely orient themselves in imposed magnetic fields and cannot respond to those fields in such a manner as to give useful nuclear magnetic signals.

The fluids that occur in earth formations, with which this invention is concerned, are petroleum oils, petroleum gases, and water. It happens, as a phenomenon of nature, that the number of protons per unit liquid volume of liquid petroleum oils, and the number of protons per unit liquid volume of liquid water are approximately equal, so that for the purposes contemplated by this invention, they may usually be considered equal.

The number of protons per unit volume of petroleum gas is usually much less than in oils or water; for example, it may be a thousand times smaller. It follows from these facts that if the density of responsive protons is determined in a portion of space, which space is filled with a porous rock, whose pores are filled with oil, gas and water, the determined density of responsive protons will be essentially a measure of the total liquid content of the pores of said rock. Furthermore, if the rock pore spaces happen to be full of only oil and water, with no gas, the determined density of responsive protons will be a measure not only of the total liquid content of the rock but also a measure of the amount of pore space in the rock, or what is called the art, the porosity of the rock.

The embodiment of the invention illustrated in Fig. 5 is particularly directed to a system for determining liquid content, or the porosity, of earth formations such as those identified as 40, 41 and 42, traversed by well bore 43. Bore hole 43, illustrated as being a well bore penetrating earth formations in search of oil, has been depicted as having irregular shape and irregular dimensions; it is filled with a drilling fluid 44 which forms a filter cake 45 along the surface of the bore hole through which some of the liquid phase of the drilling fluid may penetrate formations 40, 41 and 42.

As further shown in Fig. 5, the logging instrument is in a position to measure the density of responsive protons in the formation 41, the polarizing coil 15 being opposite formation 41. A strong direct current is passed through coil 15 for a period sufficient to induce a macroscopic nuclear magnetic moment in the responsive protons belonging both to the drilling fluid and the formation fluid. Power is supplied to coil 15 from source 11 through lead 37 of cable 46 and returns through ground at the sonde, the drilling fluid and mud pit 30. Then, the direct current is stopped very suddenly, as described hereinbefore by fast switch 13.

The direct current supplied by source 11 to coil 15 is suddenly stopped through operation of switch 20 by relay 18. Desirably both switch 20 and relay 18 are within a vacuum container 22 to eliminate arcing upon circuit interruption. Subsequently, the protons in the formation and in the drilling fluid will precess in the earth's magnetic field, and their precession may be detected through the oscillating magnetic signal that their motion produces in coil 15. By connecting coil 15 through switch 20 and cable lead 38 to a receiving and translating circuit, such as band pass amplifier 25, coil 15 is converted from a field generating device to a field measuring device. This conversion is made when relay 18 operates in response to push button 34 to control the power supplied by battery 32 to cable lead 36. The output of translating circuit 25 may be applied to a cathode ray tube 30, whose output is in turn recorded progressively and continuously by any suitable means, such as camera 26.

Camera 26 may also be made to record simultaneously the depth of coil 15 in the well bore by photographing a depth indicator 28, which is responsive to the length of cable 46 in the well bore. The signal observed on cathode ray tube 30 may be made semi-logarithmic, as represented in Fig. 6, by suitable circuitry in the translating circuit 23. It is to be specifically noted, however, that the logarthmic representation of the signal is a mere convenience for some kinds of logging operations. It is mentioned here for convenience and simplicity in the description of the logging process in question, but the logarithmic representation of the signal is not essential to the method and the method could be made to operate, for instance, if the signal representation were purely arithmetic.

By whatever detailed method the oscillatory signal is obtained, it should be either in a form such as that represented in Fig. 8, or an equivalent form that makes it possible to see separately the contribution to the signal from the drilling fluid, and the contribution from the fluids in the formation. If the composite signal is represented semi-logarithmically, as in Fig. 8, and if the relaxation times of the component signals are sufficiently different, it is possible to extrapolate the envelope of the formation-component back to the amplitude axis to estimate the initial value of the amplitude of the signal, A_f, from the formation fluids, as shown in Fig. 8. This amplitude, A_f, may be subtracted from the total amplitude, which is estimated by extrapolating the envelope of the total signal back to the amplitude axis. The difference between the total amplitude and the amplitude A_f is the amplitude of the signal from the drilling fluid, designated in Fig. 8 as A_d. It is understood that both of the amplitudes A_f and A_d may be converted into numbers representing the actual, arithmetic magnitudes, not the logarithms of those magnitudes. If the semi-logarithmic scale is not marked off in arithmetic numbers, a conversion may be made. The final numbers to be used in estimating liquid content or porosity are usually arithmetic.

If the fluids in the formation are not sufficiently unlike the drilling fluid, it may happen that the drilling fluid will need to be modified, in order to change the relaxation time of the protons in the drilling fluid, so that a composite signal like that of Fig. 8 will be obtained, in which the contributions of the drilling fluid and of the formation fluid are distinguishable. If such a need exists, the relaxation time of the responsive protons in the drilling fluid may be shortened by the introduction of one or more magnetic materials that exhibit paramagnetic or ferromagnetic properties. A good example of such material is the natural mineral, magnetite.

In general, said magnetic materials will be specifically added to the drilling fluid at a desired time, either during the drilling operations, or after such operations are completed. In many cases, the iron filings from drill pipe and drill bit that remain in the drilling fluid will reduce the need for such additions. Likewise, certain magnetite containing sandstones encountered in drilling will suitably treat the drilling fluid.

In order that the quantities, A_d, the amplitude of the signal from the drilling fluid, and A_f, the amplitude of the signal from the formation fluids, may be used to determine the density of responsive protons in the formation, it is necessary that two other quantities be known. One of these is an instrument constant, C, the determination of which amounts to a calibration of the logging instrument. The other is the density of responsive protons in the drilling fluid, P_d. Methods by which these two quantities may be determined will now be described. It will be appreciated that the definitions of these quantities are somewhat arbitrary and that the specific methods used for their determination should depend on the specific definitions chosen.

It is convenient to define the instrument constant C as the amplitude of the signal that would be obtained if the instrument were immersed in an infinite body of liquid having unit density of responsive protons. It is convenient also to define unit density of responsive protons as that density possessed by magnetically uncontaminated water. So, a convenient specific definition of the instrument constant C is the amplitude of the signal that would be obtained if the instrument were immersed in an infinite body of magnetically uncontaminated water, such as distilled water at standard pressure and temperature. This instrument constant may, of course, be determined during immersion of the instrument in a large, nonmagnetic vessel of water, the diameter of the vessel being many times the diameter of the instrument. The signal obtained in such a vessel will be approximately equal to the signal that would be obtained in an infinitely large vessel because the contribution to the signal of the water far away from the instrument in an infinite vessel would be negligible; all the significant part of the signal would come only from the water within a distance equal to a few diameters of the logging instrument.

After an instrument constant, C, is determined, the density of responsive protons in the drilling fluid, P_d, is determined by immersion of the instrument in the drilling fluid. This measurement also may be made in a large, effectively infinite, vessel, or it may be made in a smaller vessel, calibrated by a direct comparison between the signal intensities obtained with the instrument in said smaller vessel and the instrument in an infinite medium. If the measurement is made in an effectively infinite vessel, and if unit density of protons is defined as above, the density of responsive protons in the drilling fluid, P_d, will simply equal the ratio of the obtained signal to the instrument constant, C.

Now the necessary quantities have been defined to permit an explanation of the theory of the determination of the density of responsive protons in a formation penetrated by an irregularly shaped bore hole, which theory forms the basis of the steps involved in carrying out the present invention which permits the making of said determination.

The theory that underlies the present invention can be summarized in a few, simple, mathematical equations. Indeed, they are so simple that their very simplicity is deceptive unless their meaning is fully studied.

The basis of the theory is the physical fact that in the nuclear magnetic logging process each portion of material in the region surrounding the logging sonde gives rise to its own portion of the nuclear magnetic signal, and the individual portions of the signal are merely summed up by the logging instrument, that is, added aglebraically; but otherwise the individual signals have no effect on each other. If it is not immediately evident that this is a remarkable characteristic of the nuclear magnetic logging process, let brief consideration be given to any other known logging process, for instance, the electric logging process. In electric logging, the portion of the signal that is received from a part of the formation, say two feet away from the logging sonde, is modified by all of the formation within two feet of the sonde, because the signal is sensed by the sonde only through and because of the passage of electric currents between the part of the formation in question and the sonde, and those currents are modified by the electrical properties of all intervening material.

On the other hand, in the nuclear magnetic logging process, the magnetic signal from a distant part of the formation is attenuated primarily by geometric effects having to do with distance and shape, and for practical purposes it is not affected by what materials exist in the intervening space. The only effect neglected in this consideration is that due to eddy currents generated when the polarizing coil is switched off and those generated by nuclear precession. The effects of such eddy currents originating in either manner are negligible in the practical measurement.

The above physical fact about nuclear magnetic logging can be expressed in a simple equation for the total amplitude of signal detected by a nuclear magnetic logging sonde. If this total amplitude is A, and the density of responsive protons in a volume element dV is P, then

$$A=\int_{\mathrm{vol}} P\ G\ dV \qquad (1)$$

where the volume integral is taken over the entire volume surrounding the sonde, or for all practical purposes, merely over a volume whose diameter is of the order of 10 sonde diameters, because the remaining volume outside that volume contributes inappreciably to the signal. Equation 1 contains a quantity G which is a geometric factor associated with each volume element dV, and which specifies the diminution of contribution to the total signal that is the result of mere geometric distance.

Now, if the entire region around the logging sonde is actually divided into two distinct regions, such as a bore hole and a surrounding formation, Equation 1 can be split into two terms as follows:—

$$A=\int_{\mathrm{vol.}\ 1} P\ G\ dV+\int_{\mathrm{vol.}\ 2} P\ G\ dV \qquad (2)$$

Furthermore, if it can be assumed, for practical purposes, that in each of these two

regions, the density of responsive protons is substantially uniform, although it is different in regions 1 and 2, then Equation 2 may be simplified by placing the substantially constant proton densities outside of their respective integrals, as follows:—

$$A=P_1\int_{\text{vol. 1}} G\ dV+P_2\int_{\text{vol. 2}} G\ dV \qquad (3)$$

If this is done, it then becomes apparent that the quantities left under the integral signs, the geometric factors, themselves integrate into quantities that are, in turn, still other mere geometric factors, G_1 and G_2, characteristic of the shapes of regions 1 and 2:—

$$A=P_1\ G_1+P_2\ G_2 \qquad (4)$$

Now from the definition of the instrument constant C, which is the amplitude of the signal that would be obtained if the logging sonde were immersed in an infinite body of unit responsive proton density (e.g. water), it is apparent that the two geometric factors, G_1 and G_2, must sum to equal the instrument constant, because the amplitude of the signal obtained from such an infinite medium would be, from Equation 4:—

$$A=(1)G_1+(1)G_2=G_1+G_2=C \qquad (5)$$

In the special case under consideration here, the two regions of interest are the drilling fluid region, which may be characterized by the geometric factor G_d and the formation region, which may be characterized by the geometric factor, G_f; and in accordance with the definitions given hereinbefore, the amplitude of the signal from the drilling fluid region (d) must be:—

$$A_d=P_d\ G_d \qquad (6)$$

Likewise, the amplitude of the signal from the formation region (f) must be

$$A_f=P_f\ G_f \qquad (7)$$

But from Equation 5:—

$$G_d+G_f=C \qquad (8)$$

Equations 6, 7, and 8 are three equations in the three unknowns, G_d, G_f and P_f, the other quantities being known by measurements made as described hereinbefore. It is simple to eliminate two of the three unknowns, G_d and G_f, leaving the remaining unknown P_f, expressed in terms of the quantities that are known from the described measurements. The resulting equation is:—

$$P_f=\frac{A_f}{C-\dfrac{A_d}{P_d}} \qquad (9)$$

Equation 9 shows that the desired quantity, the density of responsive protons in the formation is equal to the amplitude of the signal from the formation divided by the difference between the instrument constant, C, and the ratio of the amplitude of the signal from the drilling fluid to the density of responsive protons in the drilling fluid. Equation 9 is the final equation showing how the density of responsive protons in the formation is related to and obtained from the other quantities measured by the apparatus of this invention.

Normally, water filtrate from a water base drilling fluid penetrates the porous and permeable earth formations, such as formation 41, along bore hole 43. Under this condition, filter cake 45 deposited on the wall of well bore 43 will contain a greater concentration of the solid material of said drilling fluid 44 than when held in suspension. Where, in accordance with a subsidiary feature of this invention, magnetite, or other solid magnetic or paramagnetic material is added to the drilling fluid to modify the nuclear magnetism signal from the drilling fluid, the initial amplitude of the signal from the freely precessing protons in both the drilling fluid and formation liquids is independent of the concentration of magnetic material. If excessive magnetic material is added to the drilling fluid, it may not be possible to make a proper measurement of the initial amplitude of the signal from the drilling fluid, because the relaxation time must be long as compared to the precessional period to make possible an exact measurement of the signal intensity. Thus, the liquid content, or porosity, of the earth formation is measured independently of the concentration of the magnetic modifying material used in the drilling fluid, provided said material is retained in the solid material of the filter cake, rather than passing into the formation.

It is to be noted that no appreciable signal will be obtained from the filter cake itself, so that its contribution to the signal will be small. Thus, a small error is introduced in the calculated formation porosity, such that it is less than the actual porosity. This error can be neglected in practical logging operations.

If too much magnetic material is added to the drilling fluid, inhomogeneity of the earth's field may result with attendant and undesirable shortening of the relaxation time of the nuclear magnetism signal from the formation. To avoid this field inhomogeneity problem, the bore hole may be drilled with unmodified fluid if necessary, and then the magnetic material may be added to the well bore shortly before the logging run.

The foregoing method of measuring the density of responsive protons in an earth formation may be modified in many of its details. Among such modifications is that of determining the initial amplitude of the nuclear magnetism signal for a standard sample of the drilling fluid, with the temperature or pressure of said sample elevated to conditions comparable to the downhole environment; both temperature and pressure may be raised to simulate such conditions, if desired.

While the method of measuring the density of responsive protons in the drilling fluid per se, as described above, includes detecting the nuclear magnetism signal with the same instrument as that used in the well logging operation, it will be understood that proton density of the drilling fluid alone may be accurately determined with laboratory equipment. Such laboratory instruments will measure the density of responsive protons in a small sample of the drilling fluid. This accurate measurement of drilling-fluid proton density is most useful after the logging sonde has been calibrated, as mentioned hereinabove, for various densities of responsive protons.

As discussed above, calibration of the logging sonde may be made by first introducing the sonde including its polarizing coil into an effectively infinite body of pure water to establish the instrument constant at the known proton density of said body. Then, to establish the density of responsive protons in the drilling fluid, the polarizing coil is immersed in a similar effectvely infinite body of drilling fluid. Alternatively, for convenience the amplitude of the nuclear magnetism signal obtained when the polarizing coil is immersed in a known volume of pure water may be compared to the amplitude obtained when the coil is immersed in said infinite body. Drilling fluid is then substituted for the pure water in said known volume and the amplitude of the signal measured. Thus, the relationship between the density of responsive protons in pure water under specified conditions and the density of responsive protons in an unknown drilling fluid is established.

It will be apparent that the total liquid content of the earth formation may be computed and logged automatically from the initial signal amplitudes of the nuclear magnetism signal measured in the bore hole for the drilling fluid and for the formation liquids. Such automatic computations are of course made in accordance with equation (9) above by recording P_f as that value derived from the measured values A_f and A_d. In each logging run, the terms C and P_d will be constants for that run as long as the drilling fluid in the well bore is substantially homogenous. Thus, the total liquid content of the earth formations along the well bore is recorded in accordance with the depth of the instrument in the bore hole. Said amplitudes may also be used to correlate between strata traversed by adjacent well bores.

From the foregoing description, it will be apparent that there is provided by the present invention a method and apparatus for determining the total liquid content, or porosity, of earth formations traversed by a bore hole that is independent of irregularities in the geometry of the bore hole. Briefly stated, said method includes the steps of independently measuring the density of the responsive protons of the drilling fluid employed in a well bore, followed by measuring and then separately identifying the amplitudes of the signals generated by responsive protons in the drilling fluid and responsive protons in fluids within the adjacent earth formation and then followed by computation of equation (9) either automatically or manually; said measurements each being made after establishment and interruption of a magnetic field in the respective responsive proton environments. Additionally, said method may include the preliminary step of adding a magnetic or paramagnetic material to the drilling fluid, and thereby permit distinction of the amplitudes of the signal from protons in the drilling fluid and protons in liquid in the formation comprising the combined signal derived from responsive protons in both the drilling fluid and the formation fluids. Total liquid content as determined with a calibrated logger from the amplitudes of the signals from said responsive protons in the formation fluids is then recorded in accordance with the depth of said formation in the bore hole.

While various modifications and changes in the invention will occur to those skilled in the art from the foregoing description, all such modifications and changes falling within the scope of the appended claims are intended to be included therein.

WHAT WE CLAIM IS:—

1. A method of locating the presence of a natural hydrogenous fluid in association with another natural hydrogenous fluid within an earth formation penetrated by a well bore, which comprises the steps of:—

(a) establishing a magnetic polarizing field in said earth formation from within said well bore to polarize the nuclei of hydrogen atoms of said hydrogenous fluids within said earth formation, said polarizing field being oriented at an angle to the earth's magnetic field within said earth formation,

(b) interrupting said polarizing field rapidly to permit said nuclei to precess about the earth's magnetic field within said formation,

(c) detecting nuclear magnetic precessional signals from said precessing nuclei, and

(d) measuring a characteristic of the detected precessional signals as an indication of the relaxation time of said hydrogen nuclei in the earth's magnetic field; whereby a comparison may be made between the indication of the relaxation time of said hydrogen nuclei in said earth formation and the relaxation time of hydrogen nuclei in a known hydrogenous fluid.

2. A method according to Claim 1, wherein said steps of establishing, interrupting, detecting and measuring are repeated at least once with a variation in said polarizing field.

3. A method according to Claim 1 or 2, comprising the additional step of introducing into the drilling fluid present within said well bore a ferromagnetic material or a paramagnetic material capable of penetrating into said earth formation, and detecting the effect of said magnetic material introduced into said drilling fluid on the measured relaxation time of said hydrogen nuclei.

4. A method according to Claim 3, wherein the magnetic material comprises finely divided magnetic particles.

5. A method according to Claim 3 or 4, wherein the magnetic material comprises a soluble paramagnetic material.

6. A method according to Claim 5, wherein the soluble paramagnetic material is molecular oxygen.

7. A method according to any one of Claims 3, 4, 5 and 6, when appendant to Claim 2, wherein said magnetic material is introduced between said original steps and said repeated step.

8. An apparatus for use in nuclear magnetism well logging which comprises a coil adapted to be positioned in a well bore for polarization of nuclei in and around said well bore and a source of DC power conductively connected with said coil, one dimension of said coil perpendicular to its axis being great in comparison to the other dimension of the coil which is perpendicular to the axis and to said one dimension, means for initiating current flow from the DC power supply to said coil, means for stopping the flow of DC power to said coil, and means for detecting nuclear magnetic precessional signals from precessing nuclei.

9. An apparatus according to Claim 8, wherein there are provided means for supporting said coil within the bore hole in such a manner that the said one dimension of said coil is substantially vertical in the well bore.

10. An apparatus according to Claim 8 or 9, in which said means for stopping said flow of DC power includes vacuum switch means.

11. An apparatus according to Claim 8 or 9, in which said means for stopping said flow of DC power includes electronic switch means.

12. An apparatus according to Claim 8, 9, 10 or 11, in which said means for detecting nuclear magnetic precessional signals includes amplifier means connectible to said polarizing coil and means for recording the signal detected therein.

13. An apparatus according to Claim 8, 9, 10 or 11, in which said means for detecting nuclear magnetic precessional signals includes a second coil positioned within said first coil and oriented perpendicular thereto and means for connecting said second coil to a recorder at least while current flow through said first coil is interrupted.

14. An apparatus according to Claim 12 or 13, in which said means for recording includes oscilloscope means for visibly displaying the nuclear magnetism signal and camera means for recording said visible display.

15. An apparatus according to any one of Claims 8 to 14, for use in measuring the transverse relaxation time of protons in and around a well bore, including means for polarizing said protons in and around the well bore by supplying polarizing current to said coil from said source of DC power for fixed intervals of time and means for measuring a characteristic of the in-phase precession of said protons after interruption of said polarizing current, whereby said characteristic may be correlated for different depths in said well bore to indicate variations in said transverse relaxation times.

16. An apparatus according to Claim 15, in which said characteristic of the in-phase precessional signal is its amplitude.

17. An apparatus according to Claim 15, in which said characteristic of the in-phase precession signal is its rate of decay.

18. An apparatus according to any one of Claims 8 to 14, for use in measuring the thermal relaxation time of protons in and around a well bore, including means for modifying the intensity of the polarizing field produced by said polarizing coil before interruption thereof, and means for indicating variations in the protonic precession as a measure of the thermal relaxation time of said protons.

19. An apparatus according to Claim 18, wherein the means for modifying the intensity of said polarizing field includes means for varying the time said DC current is applied to said coil.

20. An apparatus according to Claim 18, wherein the means for modifying the intensity of said polarizing field includes means for varying the DC current supply to said coil for similar time periods.

21. An apparatus according to Claim 18, 19 or 20, wherein the means for indicating variations in said thermal relaxation time includes means for comparing a characteristic of the in-phase precessional signal with said intensity of the polarizing field.

22. An apparatus according to any one of Claims 8 to 21, which includes means for introducing into the fluids around said apparatus, when used in a well bore, a substance capable of varying the nuclear magnetism precessional signals from protons in said fluids detected by said apparatus.

23. An apparatus according to Claim 22, in which said means for introducing is adapted to introduce finely divided solid ferromagnetic or paramagnetic material into the drilling fluid.

24. An apparatus according to Claim 23, in which said material is magnetite.

25. An apparatus according to Claim 22, in which said means for introducing is adapted to introduce a soluble paramagnetic material into the continuous water phase of the drilling fluid so that said paramagnetic material will penetrate the filter cake around the walls of the well bore and enter the earth formation pore spaces.

26. An apparatus according to Claim 25, in which said soluble paramagnetic material is molecular oxygen.

27. An apparatus according to Claim 26, in which said molecular oxygen is in the form of air.

28. An apparatus according to Claim 26, in which said molecular oxygen is introduced in the form of a chemical compound that releases said oxygen upon contact with a liquid in the drilling fluid.

29. An apparatus according to Claim 18 or any one of Claims 19 to 28 when appendant to Claim 18, for use in measuring the liquid content or porosity of an earth formation penetrated by a bore hole, which includes means for calibrating said apparatus in a body of pure water of known proton density to establish the instrument constant (C) for said apparatus, means for measuring the density (P_d) of responsive protons in the drilling fluid used in said well bore relative to pure water, means for recording the initial signal amplitudes from the drilling fluid (A_d) and from the formation liquids (A_f) when said coil is positioned in the well bore whereby the density of responsive protons in said formation (P_f) may be recorded in accordance with the equation:—

$$P_f = \frac{A_f}{C - \dfrac{A_d}{P_d}}$$

30. An apparatus according to any one of Claims 8 to 29, which includes means for correlating the depth of said apparatus in the well bore with measurements of nuclear magnetism signals detected therein.

31. An apparatus for use in nuclear magnetism well logging, substantially as hereinbefore described with reference to, and as shown in, Figures 1 and 2, or Figure 5 of the accompanying drawings.

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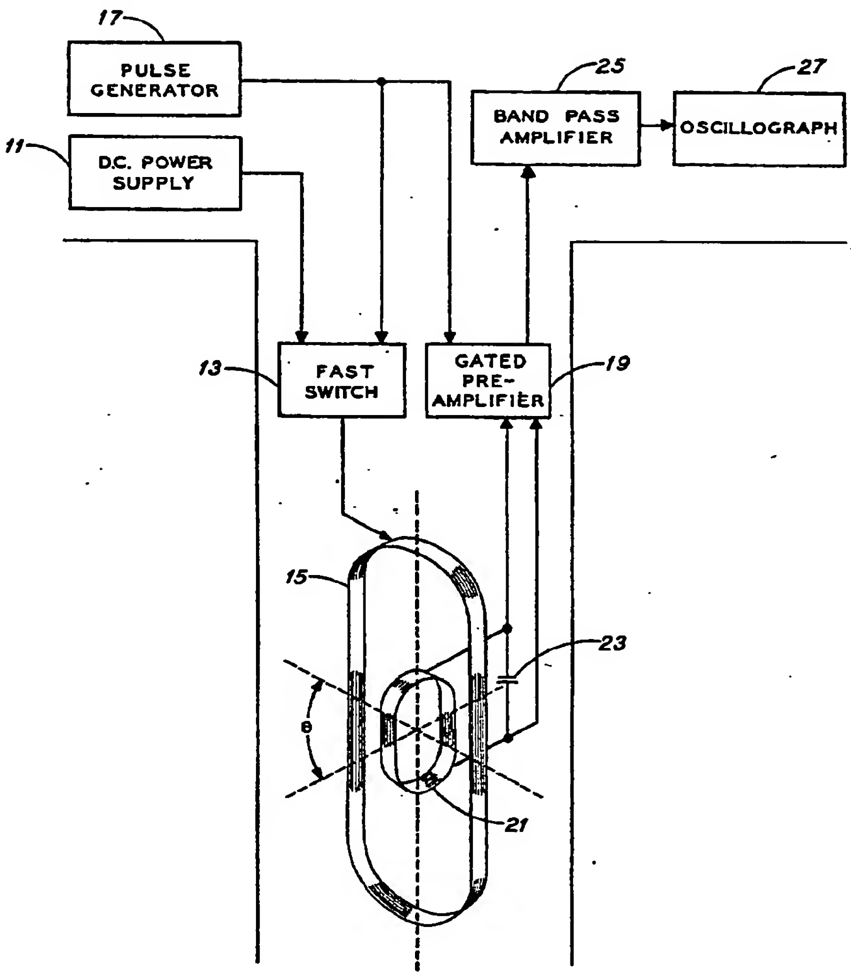
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FIG. 1

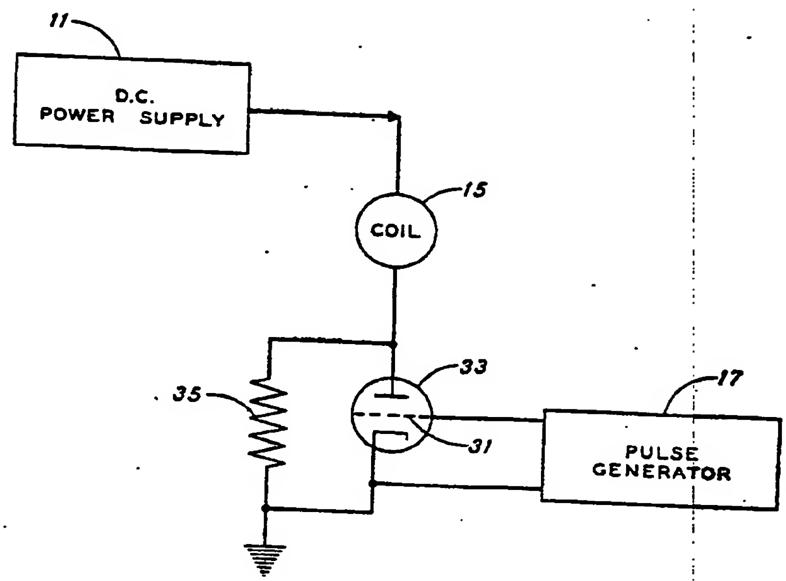


FIG. 2

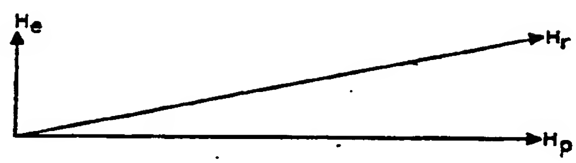
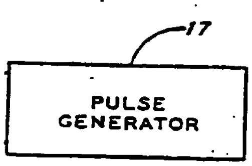


FIG. 3



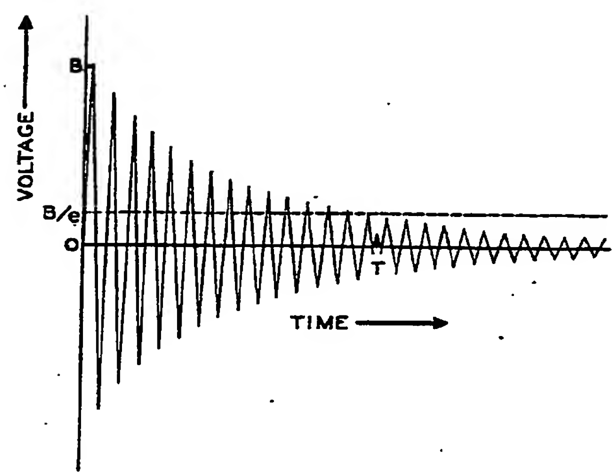


FIG. 4

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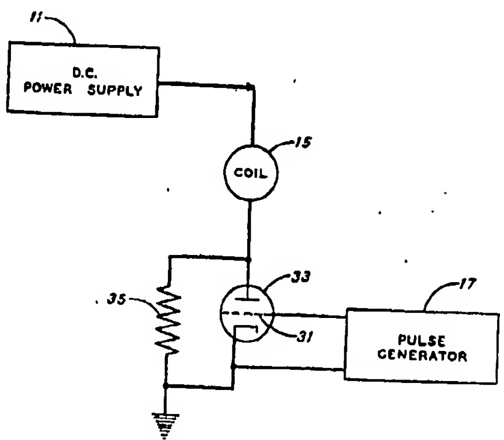

FIG. 2

FIG. 3

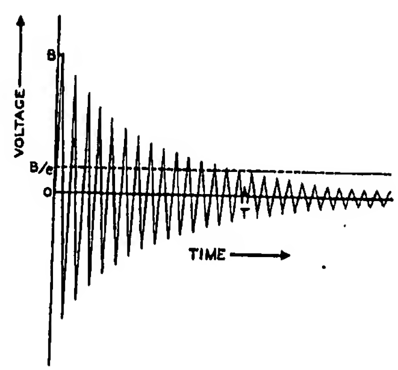

FIG. 4

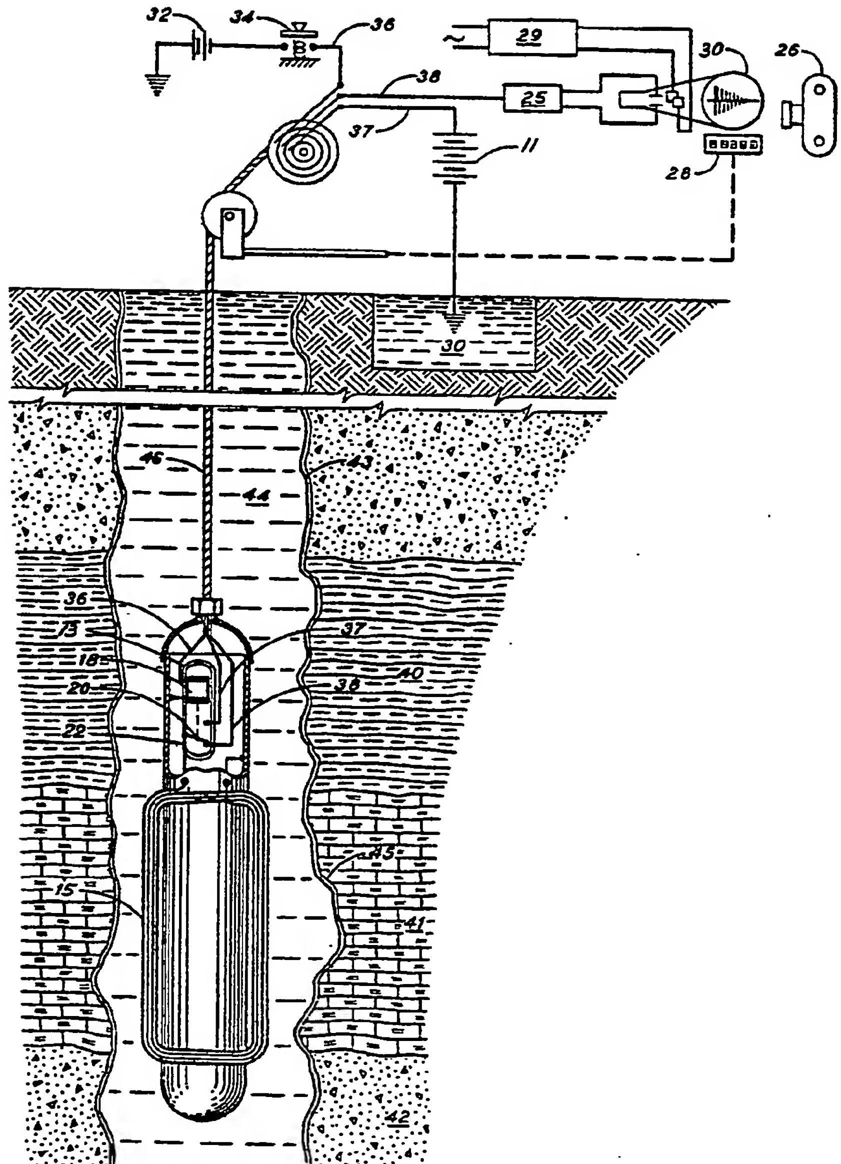

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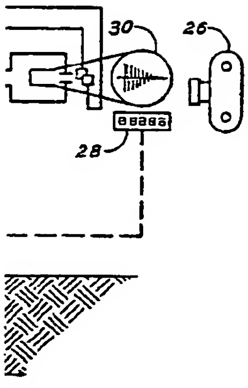
FIG. 5



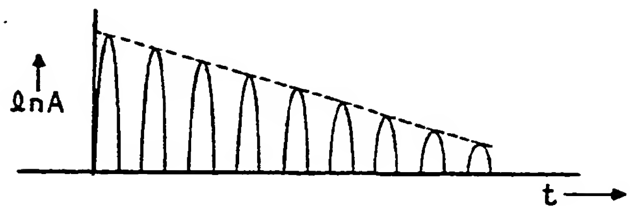


FIG. 6

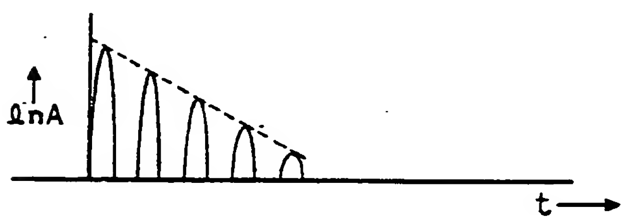


FIG. 7

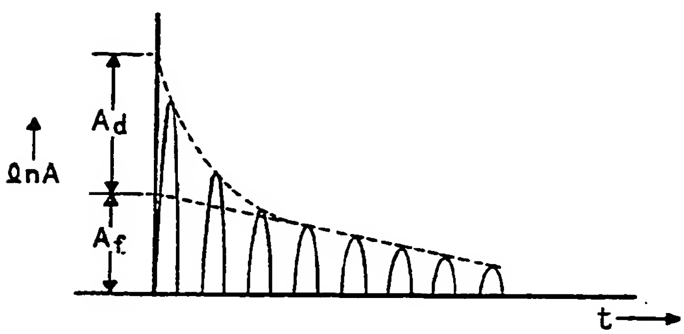


FIG. 8

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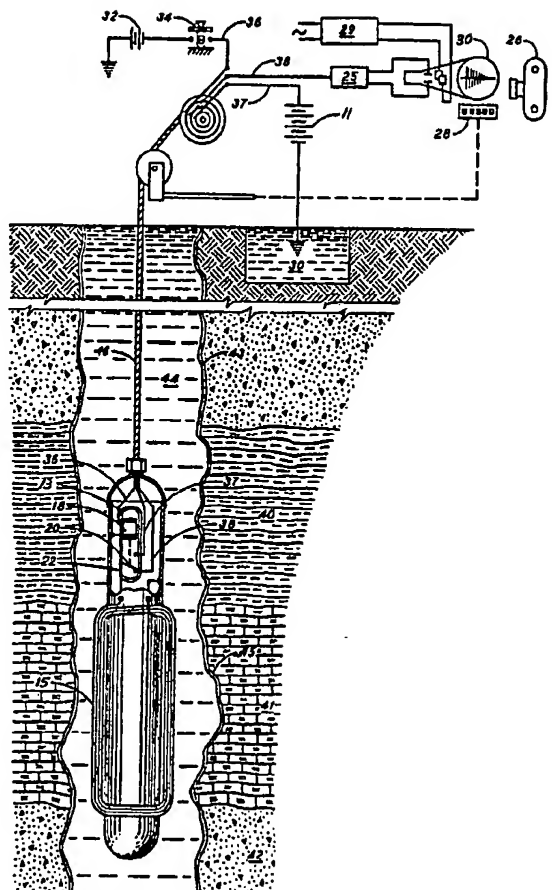

FIG. 5

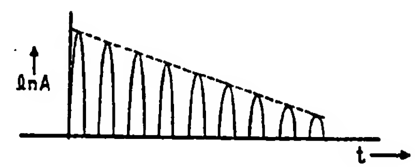

FIG. 6

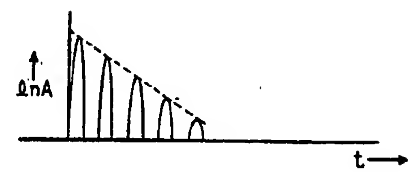

FIG. 7

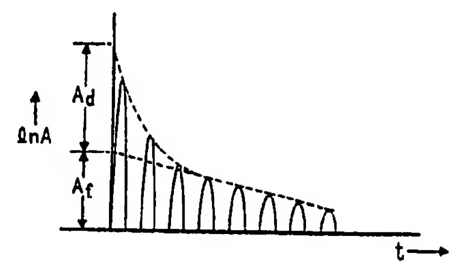

FIG. 8